THIN-FILM INTRACORTICAL RECORDING MICROELECTRODES

Quarterly Report #10

(Contract NIH-NINDS-NO1-NS-7-2364)

July - September 1999

Submitted to the

Neural Prosthesis Program
National Institute of Neurological Disorders and Stroke
National Institutes of Health

by the

Center for Integrated MicroSystems
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, Michigan
48109-2122

October 1999

Thin-Film Intracortical Recording Microelectrodes

Summary

The goal of this contract has been to develop a family of active recording probes suitable for fundamental studies in neurophysiology and for use in neural prostheses. The probes have 64 sites, of which eight can be selected for simultaneous use by the external world. On one of the probe designs (PIA-2B/3B), the neural signals are buffered and then passed directly off chip, whereas on the other (PIA-2/3) the signals are amplified, multiplexed, and then passed off chip to minimize external leads. Both two-dimensional (2D) and three-dimensional (3D) versions of these probes are being developed.

During the past term, we have continued the optimization of the probe sites for long-term in-vivo use. Polypyrrole is being explored as one possible means for improving long-term site viability in-vivo. It can be applied by an electrochemical process similar to electroplating and so can be selectively deposited on desired sites. By doping the polypyrrole with a non-immunogenic polymer such as polyethlene glycol, we may be able to prevent protein adsorption on the sites, or by use of bioactive molecules such as polystyrene sulfonate we may be able to improve the biocompatibility of the sites. The convex site topography of the polypyrrole sites may also be more optimum in interacting with tissue than the present planar sites. We are also beginning studies to determine if larger tip- or side-mounted sites (which are more similar to conventional microwires) may perform better in chronic situations because of small site-tissue motion and the mechanical removal of deposited organic material from over the site. We have also constructed chronic probe assemblies compatible with use on guinea pigs that can provide continuous bias to chronically-implanted sites. The sites, which were biased at 0.5V and –0.5V, exhibited considerable tissue growth on them after three weeks in guinea pig. Further studies will be done at lower voltages.

We have continued to optimize circuitry for use in a wireless probe interface. Circuitry for power-on-reset, clock generation, envelope detection, and voltage regulation has been redesigned to decrease power consumption and has been layed out in 1.6μm technology consistent with a popular MOSIS process. The total power dissipation of these blocks is now only 3.5mW. Fabrication of additional wafers containing PIA-2B/3B probes has also been completed. A problem leading to low-yield on some of these wafers was traced to incomplete etch of the polysilicon leads connecting the shank sites to the input site selection circuitry. The etch will be lengthened on future runs to eliminate the problem. The 96-site buffered probes also fabricated on these wafers have been tested in-vitro and in-vivo and will soon be provided to external users. In the meantime, we are iterating the PIA-2B masks to make minor circuit changes and add preamplifiers with gain in place of the present buffers. We are also proceeding to complete redesign of the circuitry for PIA-2 and PIA-3, our multiplexed recording probes.

Thin-Film Intracortical Recording Microelectrodes

1. Introduction

The goal of this program is the realization of batch-fabricated recording electrode arrays capable of accurately sampling single-unit neural activity throughout of volume of cortical tissue on a chronic basis. Such arrays will constitute an important advance in instrumentation for the study of information processing in neural structures and should also be valuable for a number of next-generation closed-loop neural prostheses, where stimuli must be conditioned on the response of the physiological system.

The approach taken in this research involves the use of solid-state process technology to realize probes in which a precisely-etched silicon substrate supports an array of thin-film conductors insulated above and below by deposited dielectrics. Openings in the dielectrics, produced using photolithography, form recording sites which permit recording from single neurons on a highly-selective basis. The fabrication processes for both passive and active (containing signal processing circuitry) probe structures have been reported in the past along with scaling limits and the results of numerous acute experiments using passive probes in animals. In moving to chronic implant applications, the major problems are associated with the preserving the viability of the sites in-vivo (preventing tissue encapsulation of the sites) and with the probe output leads, both in terms of their number and their insulation. The probe must float in the tissue with minimal tethering forces, limiting the number of leads to a few at most. The encapsulation of these leads must offer adequate protection for the meg-ohm impedance levels of the sites while maintaining lead flexibility.

Our solution to the lead problem has involved two steps. The first has been to embed circuitry in the probe substrate to amplify and buffer the signals and to multiplex them onto a common output line. Using this approach, signal levels are increased by factors of over 100, impedance levels are reduced by four orders of magnitude, and the probe requires only three leads for operation, independent of the number of recording sites. A high-yield merged process permitting the integration of CMOS circuitry on the probe has been developed, and this circuitry has been designed and characterized. The second step has involved the development of silicon-based ribbon cables, realized using the same probe technology, to conduct the neural signals to the outside world. These cables have shown significant advantages over discrete leads, both in terms of the ease with which chronic implants can be assembled and in terms of the ability of the cables to survive long-term biased soaks in saline. The cables can be built directly into the probes so that they come off of the wafer as a single unit, requiring no joining or bonding operations between them. The cables are also significantly more flexible than previously-used discrete wire interconnects.

This contract calls for the development of active probes for neural recording. A 64-site 8-channel probe with site selection and signal buffering but no multiplexing has been developed (PIA-2B) along with a high-end multiplexed probe that includes gain (PIA-2). During the past quarter, we have done the following: 1) we have continued to fabricate passive probes for internal and external users; 2) we have continued to explore the use of polypyrrole recording sites as a way to improve long-term site viability; 3) we are developing a new set of passive probes to better understand the role of site size and position in chronic recording viability; 4) we are continuing to examine the role of bias in the long-term tissue reaction to the presence of sites; 5) we have continued to refine circuitry for leadless probe operation; and 6) we have continued to test and optimize completed two- and three-dimensional active PIA-2B/3B recording probes. Work in these

areas is discussed in the following sections. In addition, it should be noted that during the past six months we have had considerable turnover in the student personnel active in this project and the companion Stimulating Electrode project. Tracy Bell, who explored the development of alternative micromachining processes for probe fabrication and developed a prototype cochlear electrode to validate the process, graduated and is now employed at Hewlett-Packard Corporation. Qing Bai, who developed and characterized active recording probes, graduated and is now employed at Guidant Corporation. Finally, Arjun Chandra, who developed the use of an input MOSFET clamp device for input stabilization and began the work on the telemetry interface for the probes, has also departed and is employed at IDT Corporation. Roy Olssen has joined the program to work on the development of PIA-2/3 and the associated platform multiplexing circuitry, Hao Yu has taken over the telemetry task, and Ying Yao has joined the Stimulation project to complete the development of STIM-2/3.

2. Long-Term Stable Recording Sites Passive

In a joint activity between the Neural Prosthesis Program, the CNCT grant, and the UM Material Science and Engineering Department, we have been exploring various approaches to improving the long-term viability of our recording sites. This is in response to the problem seen in the chronic use of planar recording sites wherein the site recordings are gradually lost over a period of days to weeks even as the site impedance gradually increases. Electrode sites at the ends of microwires or on the inside edges of sieve probe holes seem less prone to this loss in recording ability over comparable periods. There are two major approaches which we are pursuing to better understand and solve this recording deterioration problem. Both hypothesize that an insulating layer of organic material builds up and obstructs the electrode site surface over time.

The first approach to solving this problem is to develop a method whereby the buildup of the obstructing layer can either be prevented or reversed by electrical or mechanical erosion. Electrical erosion has been investigated both by *in vivo* experimentation,[1,2] and by a combination of experimentation and simulation[3]. Passage of electrical current through sites that have lost much of their recording ability tends to reduce the impedance of the site and sometimes, but not always, restores unit-recording characteristics. It is surmised that the current punches a hole in the organic overcoat, which lowers the site impedance and may or may not allow access to the ionic current flow that surrounds nearby active cells. It is unknown whether ac high-frequency currents might do better at removing such films than dc currents. Certainly they would minimize the effect of the double layer and concentrate more on the film to be removed, which should disrupt the spreading resistance near the site. A convex site may also be helpful in more uniformly concentrating any “cleaning” currents over the site surface.

We are designing a mask set to explore such effects. Microwires, which have large sites (400-2000μm^2) situated at the very tip of the associated structure, are reported to see less degradation effects than we have experience with our planar sites. However, it is

---

[1] J.F. Hetke, D.J. Anderson, J.A Wiler and B.M. Clopton, "Chronic Multichannel Recording from Guinea Pig Inferior Colliculus," *Abstracts, 1992 Association for Research in Otolaryngology,* St. Petersburg, Feb. 1992.

[2] E.M. Schmidt, W.J. Heetderks and D.M. Camesi, "Chronic Recording from Cortical Areas with Multicontact Silicon Probes," *Abstracts, 1993 Society for Neuroscience*, Washington D.C., Nov. 1993.

[3] K. Oweiss, M. Wise, C. Lopez, J. Wiler and D. Anderson, "Chronic Electrode-Brain Interface Modeled with FEM," Abstracts, Joint meeting of the BMES and EMBS, Atlanta, Oct. 1999.

perhaps not surprising that a 100μm^2 planar site in the middle of a flat carrier would see more protein buildup and thus degrade more rapidly. The probes on this mask set will be designed for chronic implantation using ribbon-connected surface platforms and will feature large tip-mounted sites as well as large and small sites situated along the edges and along the center-line of the probe substrate. Thus, we hope to track the impedance and recording abilities of these sites and make a more realistic comparison with microwires. It is known from histology that near the tip of implanted probes there is significant movement of the probe with respect to the tissue which may tend to remove films from such sites. To a lesser degree, micro-motion may also help remove it near the edge of the probe. We hope to clarify the effectiveness of electrical and mechanical stimulation on removing surface films from the sites with this mask set during the coming quarter. We will also attempt to perform previously-proposed "artificial neuron" experiments in which we will record from stimulating sites positioned on adjacent shanks a known distance from the recording sites. This will allow us to eliminate the possibility that recording ability is lost because cell activity is falling off rather than because of any degradation in the probe-cell connection.

The second approach to improving chronic site viability involves the idea that preventive actions against the build-up of the obstructing layer can be taken by designing the chemistry of the probes to discourage the adsorption of proteins. The following work, being carried out in collaboration with Dr. David Martin of the UM Materials Science and Engineering Dept., addresses the second of these hypotheses.

The molecular approach to the chronic recording problem consists of two hypotheses: 1) if the failure is simply caused by closure of the electrode site by physical deposition of protein or tissue, a film or an ingredient of the recording site material which prevents protein adsorption should be incorporated into the site design; and 2) if the failure is due to the self-protection response of the subject, some bioactive molecules should be put onto the site to improve the biocompatibility. Both ideas for prevention of site blocking can be realized by incorporating polyelectrolytes in a material such as polypyrrole which is used for the electrode sites. We have done experiments to prove that this can be done by simply replacing the 'dopant' we have been using in the electro-polymerization of polypyrrole, polystyrene sulfonate, with bioactive molecules such as collagen and synthetic protein SLPF, respectively. Collagen is well known as an extracellular matrix protein that is often added to cell culture media. SLPF is a genetically synthesized silk-like protein polymer that contains a high concentration of the RGD amino acid sequence, the cell binding sequence of fibronectin. Microscopic IR data indicate that the bioactive molecules are incorporated into the polypyrrole films on the electrodes. The response of nerve cells to the polypyrrole/ bioactive molecule composites is being tested in cell culture in the laboratory of Yehoash Raphael of the Kresge Hearing Research Institute. Figure 1, repeated from the last report, shows a probe with both iridium oxide and polypyrrole sites.

Polyethlene glycol (PEG) is well known as a non-immunogenic polymer that prevents protein adsorption. We have tried to put PEG onto the electrode using the same method as described above. To identify PEG from IR spectroscopy, however, is difficult. We currently do not have definitive evidence of PEG's presence on the electrode with polypyrrole but are working on it.

Thus, polypyrrole doped with appropriate additives is a second approach being explored for long-term stable recording sites. Although polypyrrole also provides a low-impedance surface for microstimulation, it is primarily in a recording role that it is being explored at present. It will be deposited on the probes from the new mask set to allow another dimension in the investigation of site stability.

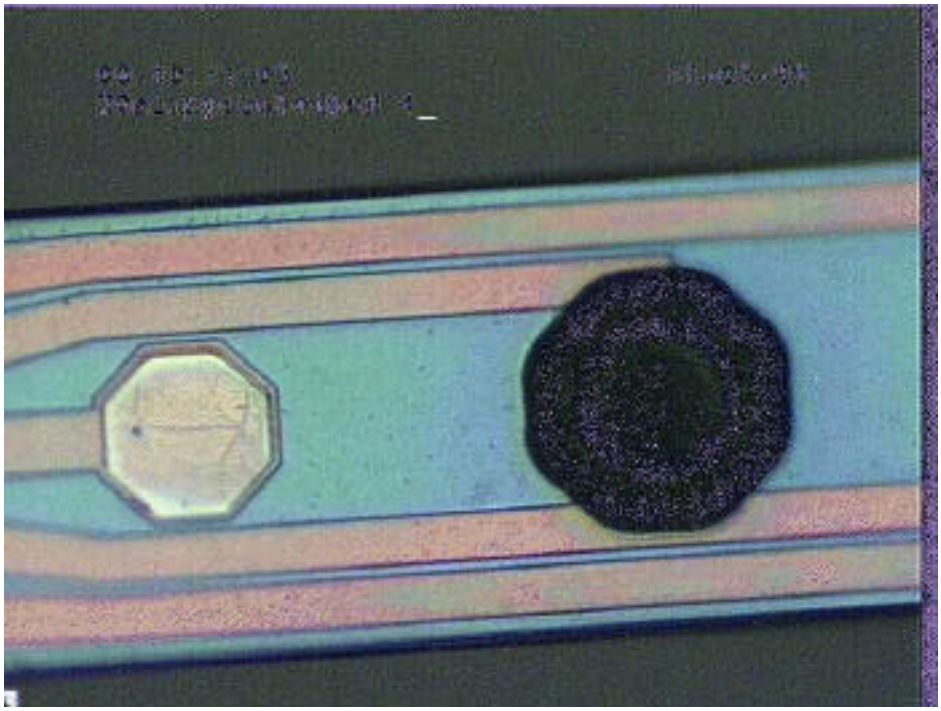

Fig. 1: Iridium oxide and polypyrrole sites on a passive probe. The polypyrrole is deposited by an electrolytic process so the deposit can be selective, depending on which site or sites receives current flow. Making electrodes for comparison experiments is therefore a simple post-processing step.

3. Chronic biasing of passive probes

In the previous quarterly report, we stated that we were going to implant a guinea pig with a passive chronic electrode and continuously apply a 0.5Vdc bias through one of the sites. We have often observed a reduction in impedance and a restoration of unit recording after applying a small DC voltage to chronic sites. Our thoughts here were that by applying a continuous DC voltage to the site we might suppress the build-up of organic films there and maintain more stable long-term unit recordings. In addition, continuous bias is often recommended for stimulating sites to increase the voltage excursion permitted inside the water window. Jim Weiland (J. D. Weiland. Electrochemical Properties of Iridium Oxide Stimulating Electrodes. Ph.D. Thesis, The University of Michigan. 1997) found that he could achieve better charge transfer by biasing the site between stimulation pulses. He chronically implanted guinea pigs with stimulating electrodes and stimulated the animals 2 hours per day for five days. A positive bias of 0.5V was maintained on the sites between pulses. We implanted both positively 0.5V (pos1, pos2) and negatively 0.5V (neg1, neg2) biased sites in guinea pigs. For the positively-biased animals, the bias was applied to a 3mm linear array probe between channel 1 and ground; for the negatively-biased animals, the bias was applied between channel 4 and ground. Regular impedance measurements were taken. Although the sites did not increase to the 8-10 MΩ impedance range that we typically see, there was no clear difference between the biased and the non-biased sites from which to draw any definite conclusions More data needs to be taken.

The amount of current applied by this method was less than could be measured with our equipment (<10 nA).

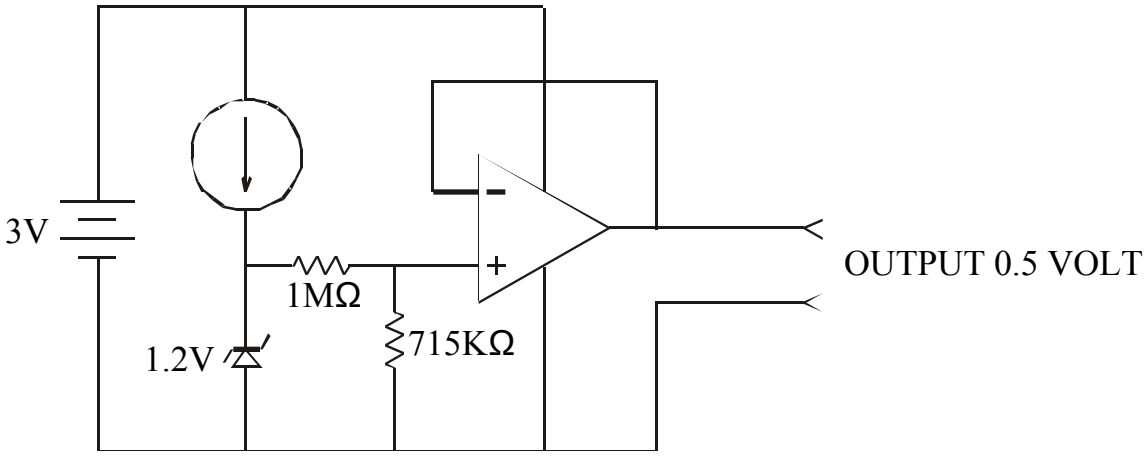

Fig. 2: Circuitry used for chronic biasing of implanted sites. The circuitry was contained on a small head-mounted circuit board worn by the animal.

Upon histological examination of the tissue surrounding the biased implant (Fig. 3), there was considerable damage to the tissue especially near the biased site. A large portion of tissue was removed with the electrode; with non-biased sites, we get little to no tissue adherence and often see electrode features, such as poly lines indicated in the tissue.

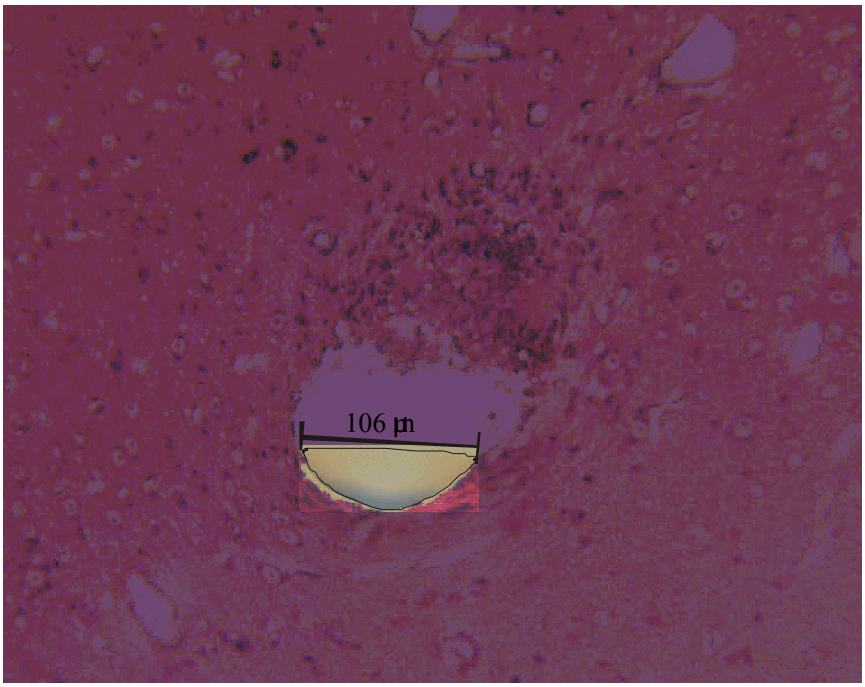

Fig. 3: Cross-section through the biased region of tissue near site Pos1. Note the large region of tissue removed with the probe. The grey shaded area represents the area of the removed probe. The implant time was three weeks.

Scanning electron microscopy (SEM) shows this increase in tissue adherence to the biased site is similar to what we saw for the chronic stimulating electrodes of Weiland. From these results, it is evident that the voltage applied was too great; we plan to repeat these experiments using lower voltage levels to explore these effects further during the coming quarter.

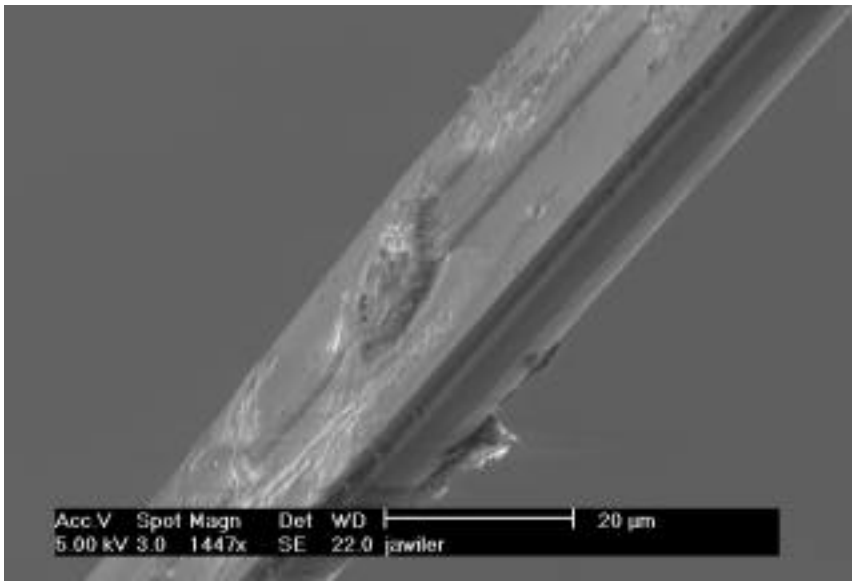

Fig. 4: SEM view of the effects of –0.5Vdc bias applied through site 4. Note the neural tissue adhering to the site. The implant time was three weeks.

4. Development of a Wireless Probe Interface

This project seeks to develop a wireless interface to one or more probes consistent with eliminating the need for a percutaneous plug and internal ribbon cable. The circuitry would be mounted on the surface platform holding the probe array in most cortical applications. Over the last quarter, work has been carried on the following tasks: 1) We have redesigned the analog front-end circuit blocks of the telemetry system to lower its power dissipation; 2) We have simulated the above circuits extensively; and 3) We have modified the AMI ABN process from a minimum feature size of 1.2µm to a feature size of 1.6µm. A description of this work is given in the following sections:

4.1 Design of the circuit blocks of the telemetry system

The telemetry system imposes some very strict demands on the circuitry in terms of power dissipation, and some of the circuits already designed have not reduced power levels adequately. Thus, additional research was needed to lower the system power dissipation to acceptable levels. The following sections describe this process.

Power on Reset

As shown in Fig. 5, the Power-On-Reset circuit is composed of a high-pass filter and a Schmitt Trigger (M1-4).

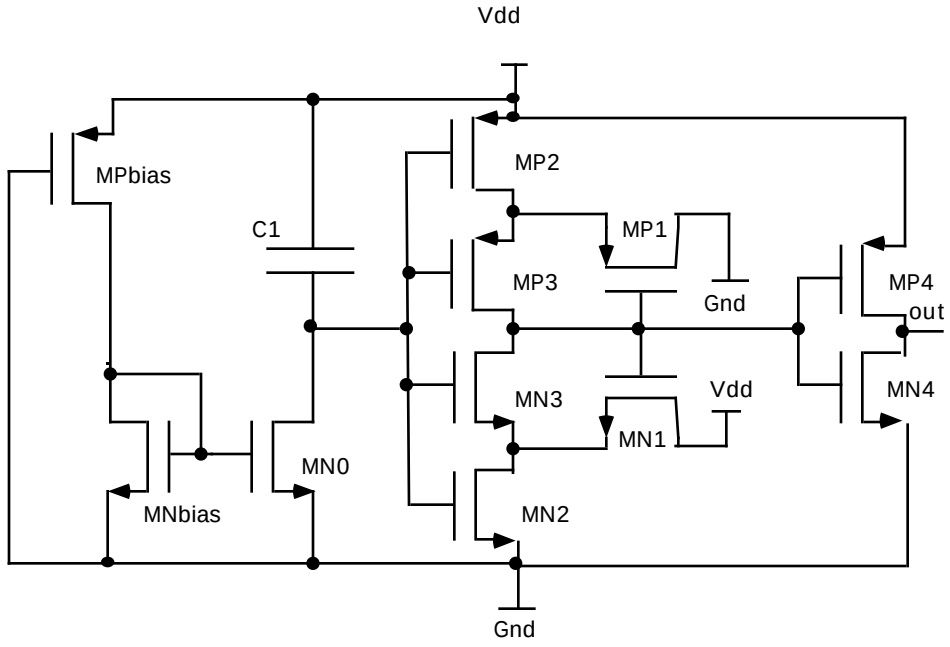

Fig. 1: Power-On-Reset Circuitry

Capacitor C1 and NMOS MN0, which is biased through MPbias and MNbias, form the high pass filter. The output of this filter is fed to the Schmitt Trigger in order to clear the unnecessary effects of noise. At the time of power-on, the output of the POR rises to the high state and stays there for a short time, then returning to the low state when C1 has charged. The size of MN0 and the capacitance C1 were chosen to set the width of the high output voltage to about 60µs. The simulated response is shown in Fig. 6. The power dissipation of this block has been decreased from 2mW to 150µW.

Clock generator

The clock generator is shown in Fig. 7. In this circuit, the RF signal from the receiver coil is passed through the half-rectifier and is divided by C1 (1p, upper) and C2 (5p, lower). The AC signal on C2, with an amplitude of one sixth that of the input RF signal, is fed to inverter X1 (left) and then X2 (middle). X3 (right) is a very weak inverter used to set up the quiescent voltage of point A through feedback resistor Rfd. Cascode MOS devices are used to discharge the capacitors C1 and C2, where a cascode is used to ensure a high breakdown voltage for the circuitry. The output simulation for the clock generator is shown in Fig. 8. The power dissipation of this block is only 0.5mW from Vdd and 0.5mW for an RF signal with an ac amplitude of 20V.

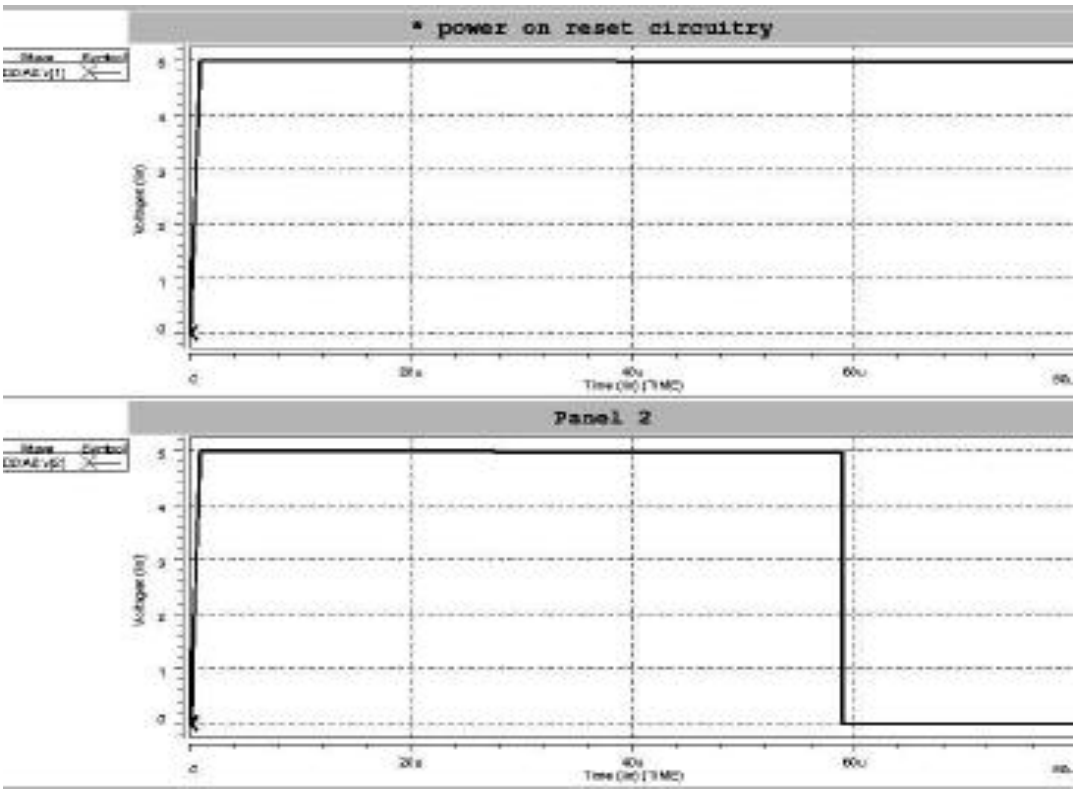

Fig. 6: Simulated output of the POR

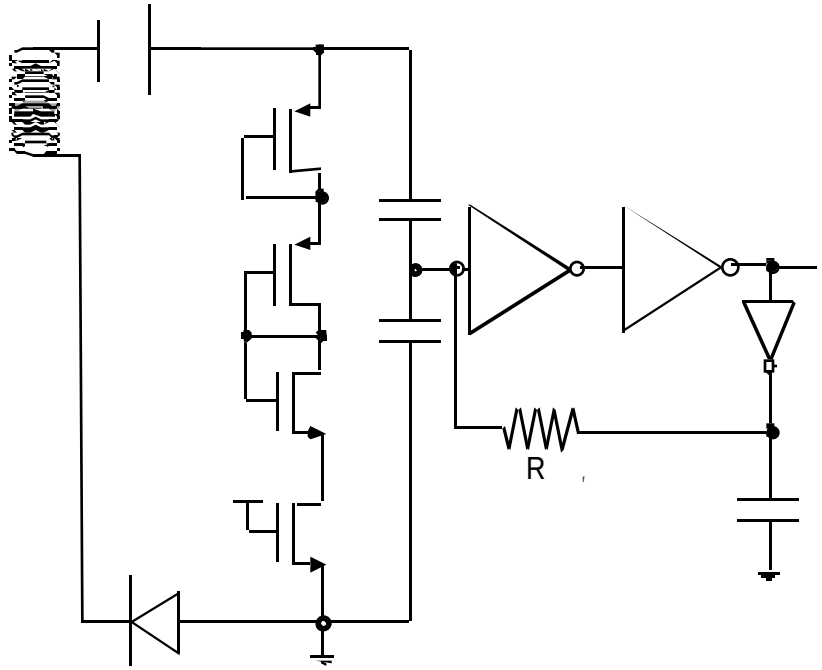

Fig. 7: The schematic of clock generator.

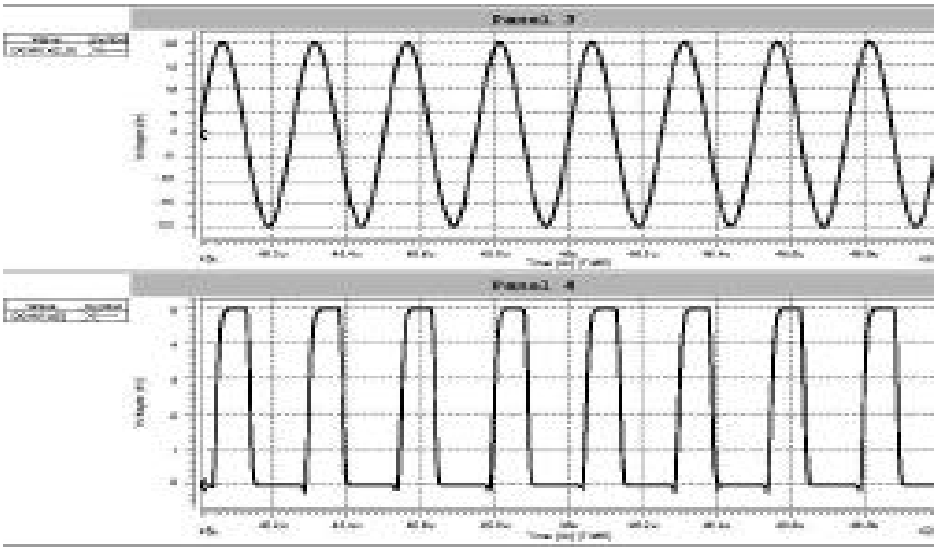

Fig. 8: Simulation results for the clock generator

Envelope detector

The schematic of the envelope detector circuit is shown in Fig. 9. This circuit is composed of a low-pass filter followed by a high-pass filter and Schmitt trigger. In this circuit, the high frequency components in the received RF signal are attenuated by the filters before entering the Schmitt, which can suppress the effects of noise. The low-pass frequency cut-off is determined by MNflt, MPflt and C2, and the high-pass frequency cut-off is dependent on C1, MNbias and MPbias. The power dissipation of this re-designed block is only 0.355mW from Vdd instead of 5.3mW in the old design.

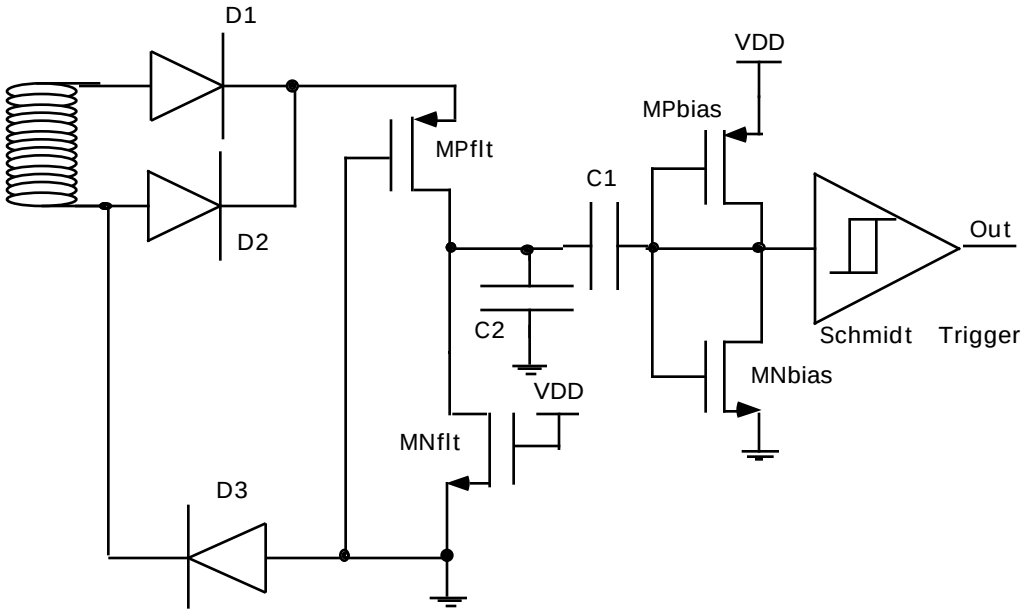

Fig. 9: The schematic of envelope detector

Voltage Regulator

The schematic of the voltage regulator is shown is Fig. 10. The accuracy of VDD satisfies the demands of the 8-bit ADC, and the degree of temperature independence and power supply rejection in the circuit are very attractive. Moreover, the total power dissipation of the regulator is only 2mW, including the power directly from Vpwr .

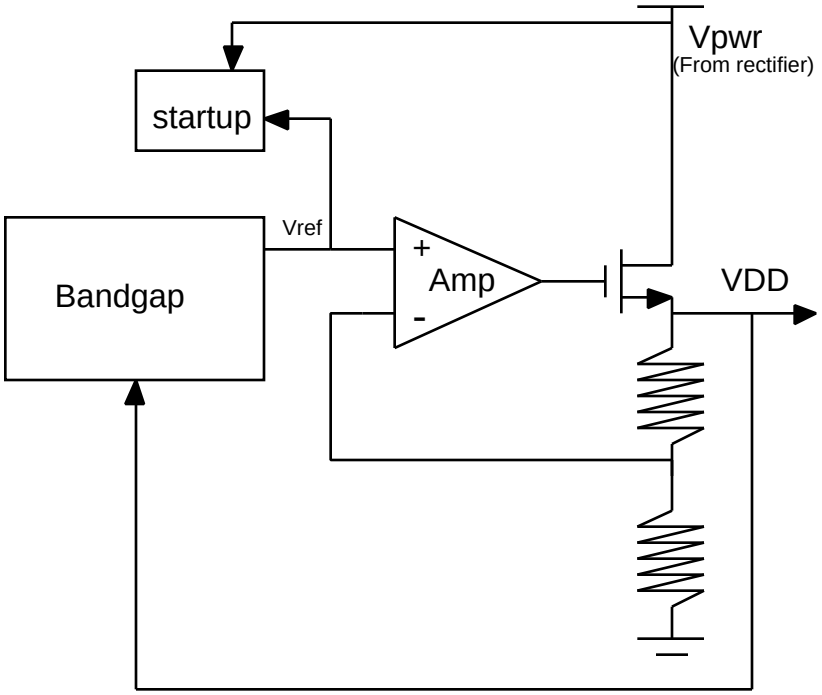

Fig. 10: The schematic of voltage regulator circuit.

4.2 Circuit Implementation

The AMI ABN process was chosen for the implementation of the telemetry circuits using the MOSIS foundry. Currently, a design lambda of 0.8μm for the AMI ABN process is recommended by MOSIS to improve consistent and uniform electrical behavior for both analog and digital designs. Moreover, the processing (run) frequency of the process based on the new design lambda will be increased to 12 runs per year so that more opportunities can be obtained to fabricate our circuits. Considering the above advantages, we have shifted our design rules to the new recommendations. The MOSIS ABN process offers two metal layers, two polysilicon layers, and an optional BJT NPN device; thus, the devices that can be used in circuit design include PMOS, NMOS, capacitor, resistor, diode, NPN and substrate PNP BJTs.

During the coming quarter, we plan to pursue the following goals:

1) Complete the design of all of the analog telemetry circuits, including the voltage regulator, envelope detector, clock recovery, power-on-reset and preamplifier. The simulations should be carried out to include reasonable threshold voltage variations, power supply voltage variations, and

temperature variations in order to guarantee the correct function and satisfactory performance of the circuits. In the design of these circuits, the breakdown voltage of the MOS devices should be taken into account since the induced RF signal in receiver coil may be very high when the distance to transmitter becomes very short.

2) Complete the layout of the circuits and send it to MOSIS for fabrication.

3) Start the design of the ADC and the total telemetry platform.

The architecture of the telemetry system is shown in Fig. 11.

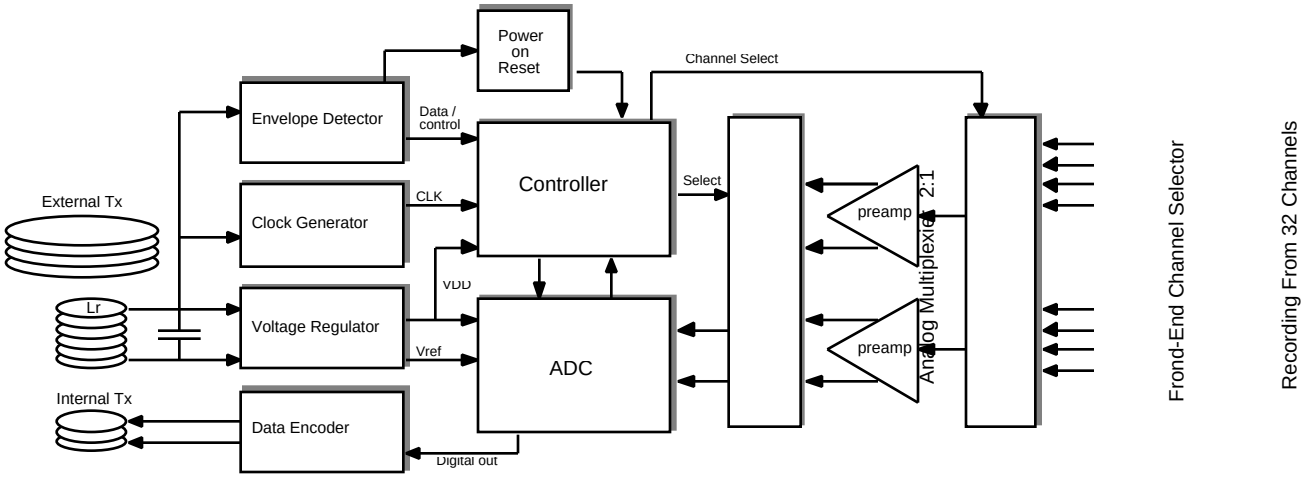

Fig. 11: The schematic of the entire telemetry chip

4. Development of a 64-Site Eight-Channel Non-Multiplexed Recording Probe (PIA-2B)

The architecture and design of a 64-site front-end-selected, buffered probe have been discussed in previous quarterly reports. During the past quarter, work has primarily focused on testing of the fabricated probes. All circuitry has been found to function correctly on these probes, although on some wafers a processing error was made during fabrication which lowered yield and resulted in the polysilicon leads from the recording sites being shorted together where they enter the circuit area. It was important to understand this error, both to ensure it is corrected as additional wafers are processed and to eliminate design errors as a possible mechanism for the yield loss.

During the in-vitro testing of the probes, it was found that there was excessive crosstalk between separate recording sites. This crosstalk was at first thought to originate in the circuitry; however, testing verified that the front-end selection and buffer circuitry were functioning correctly. The problem was finally isolated by making a series of laser cuts along adjacent polysilicon lines and measuring the impedance between the lines as illustrated in Fig. 12 below. In this photo, the polysilicon lines coming from the sites into the front-end selector are running vertically. When the polysilicon line was cut at location A only (above a significant step in the field oxide), the electrical resistance between the

lines remained low, but when a cut was made at location B (below the step) an open circuit was created between adjacent lines. In this way, we were able to determine that there a fairly high resistance (40-80kΩ) was shorting the lines together along the base of the step. The problem did not involve any of the devices or circuits, but was thus a processing problem.

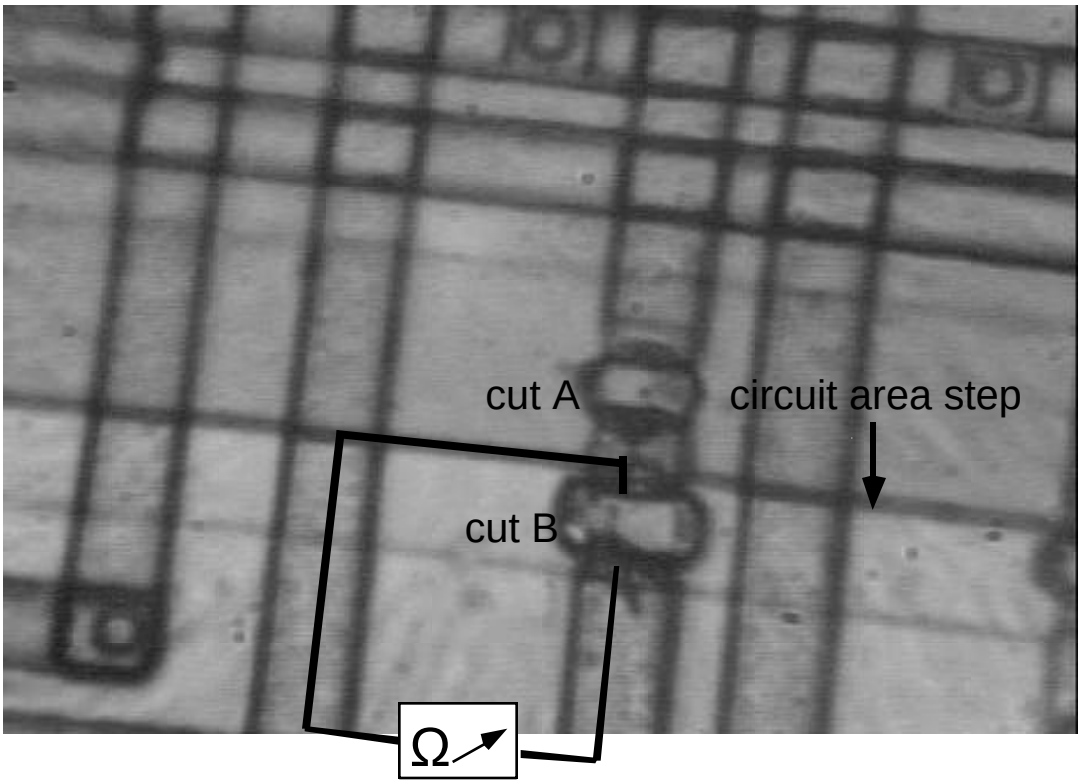

Fig. 12: Use of laser cutting to isolate a polysilicon short at the base of a step in the field oxide at the base of the site selection circuitry.

The cause of this short was found to be a thin ribbon of residual polysilicon at the base of the step into the circuit area. During the chemical vapor deposition (CVD) of polysilicon, the deposited film is thicker in the region of a step due to the conformal nature of the deposition; it is deposited on the side of the step in addition to the horizontal surfaces. After CVD, the polysilicon is patterned using reactive ion etching (RIE), which is a directional etch from the top. The thickness of the polysilicon is larger along the vertical direction of the step than on the horizontal plane of the wafer, a fact that is sometimes used in circuit fabrication to create "sidewall spacers" in advanced device structures. To ensure removal of such spacers, the RIE etch must be longer than is required to just remove the film over the horizontal field regions of the chip. This is shown in Fig. 13 below. The desire to overetch must be balanced against the lack of perfect selectivity between the mask and the film (mask erosion) and against the tendency to undercut MOS gate lengths, which would alter circuit performance. There is a sufficient process window to avoid both the spacer problem and gate length alterations, but closer monitoring of the poly etch at areas of large step heights is necessary. The current method of verifying etch completion is to electrically probe an open area where the polysilicon has been etched to verify that an open circuit exists there. Clearly it would be a good practice to probe poly lines after the photoresist has been removed to verify an open circuit between

separate lines. This will be done as future wafers are processed and is part of the learning curve not always passed from student to student. This was the first process run for the student now processing active recording probes.

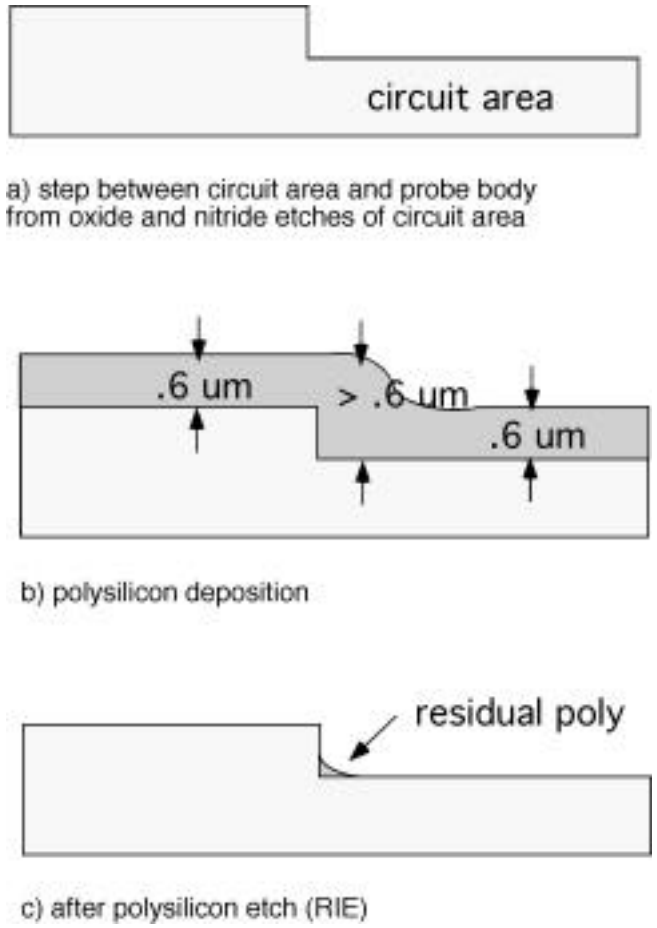

Fig. 13: Formation of polysilicon streamers due to incomplete reactive ion etching.

We are now moving to test the 8-channel 64-site non-multiplexed probes in-vitro and in-vivo. In addition, a 96-site buffered probe was included on the same mask set as PIA-2b-3B which utilized aluminum leads into and out of its smaller circuit area. Because of this, any unetched polysilicon sidewall streamers had no effect on probe operation and yields were high. (This suggests the use of aluminum shank interconnects on future probes to provide low-resistance connections between the sites and the circuitry.) In-vivo recordings from guinea pig using the 96-site buffered probe are shown below in Fig. 14. Examples are shown of both spontaneous (top) and driven activity (below.) Single-unit activity is clearly visible in these recordings, which were taken directly into an AC-coupled external preamplifier without a headstage amplifier. Further in-vivo testing and characterization of this buffered probe is planned in the coming quarter and samples will be sent to one of our external collaborators (Dr. Gyorgy Buzsaki), marking the first time we have distributed active probes to outside users.

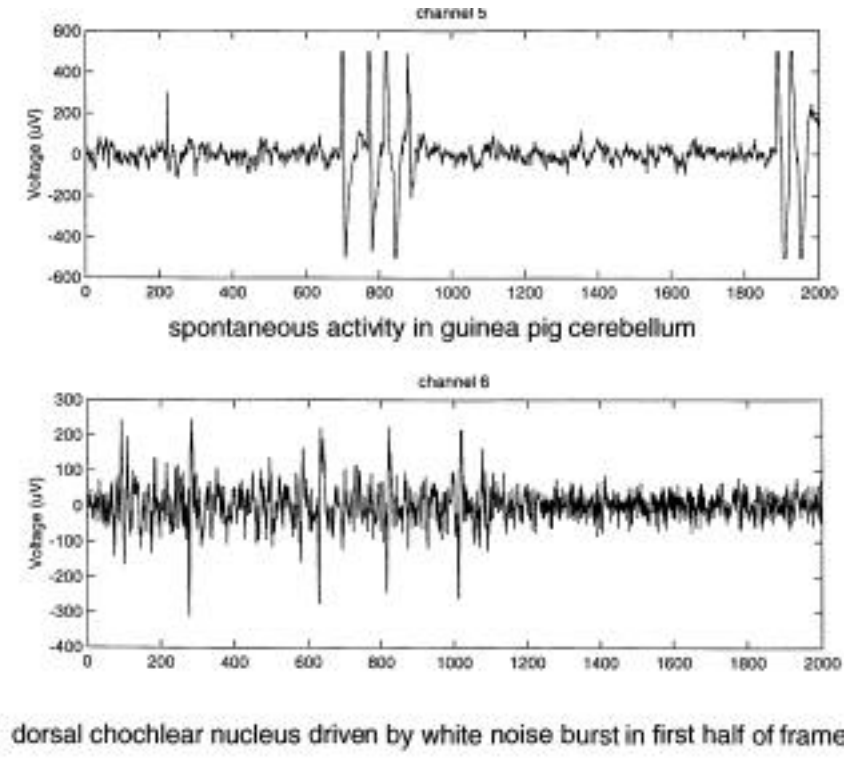

Fig 14: In-vivo recordings from guinea pig cerebellum and dorsal cochlear nucleus obtained with a 96-site buffered probe.

An additional area for current work is to explore the use of shunt resistors to stabilize the input dc bias levels at the inputs to on-chip high-gain recording preamplifiers. The present probes have only unity-gain buffers, so gain stabilization is not a problem; however, on future versions of PIA-2B we will be substituting higher-gain (100X) preamps for the present buffers. We have shown previously that shunt resistors from the input lines to ground with resistances between about 80kΩ and 500kΩ are needed. The low-end value is set by the need to maintain the low-frequency cutoff of the recording bandwidth significantly below 100Hz (typically about 10Hz), while the high-end limit is set by the need to quench optically-induced noise currents at the preamplifier inputs with no more than a millivolt (typically <100μV) of resulting offset. We have shown that shunt MOS transistors operated in the subthreshold region can provide such resistances without excessive process sensitivity. The use of resistances would also provide small clamping devices while perhaps having less optical sensitivity since they would be on top of the field oxide and would be optically shielded by a metal overlay. We have now completed process simulations of the fabrication of such devices using ion implantation through oxide to dope the needed devices. Experiments to be performed during the coming quarter will show whether it is in fact possible to fabricate such resistors in our process with adequate reproducibility and control. Either clamping resistors or shunt MOSFETs will be used with all future preamplifier designs to eliminate offset problems from our amplifiers. The design of revised circuitry to be used on PIA-2/3 is also now beginning.

Work during the coming quarter will focus on making some minor changes to the mask set to allow increased testability of PIA-2b, on adding amplifiers to some of these probes, and on continuing their fabrication. Final design of PIA-2 will also be underway.

5. Conclusions

During the past term, we have continued the optimization of the probe sites for long-term in-vivo use. Polypyrrole is being explored as one possible means for improving long-term site viability in-vivo. It can be applied by an electrochemical process similar to electroplating and so can be selectively deposited on desired sites. By doping the polypyrrole with a non-immunogenic polymer such as polyethlene glycol, we may be able to prevent protein adsorption on the sites, or by use of bioactive molecules such as polystyrene sulfonate we may be able to improve the biocompatibility of the sites. The convex site topography of the polypyrrole sites may also be more optimum in interacting with tissue than the present planar sites. We are also beginning studies to determine if larger tip- or side-mounted sites (which are more similar to conventional microwires) may perform better in chronic situations because of small site-tissue motion and the mechanical removal of deposited organic material from over the site. We have also constructed chronic probe assemblies compatible with use on guinea pigs that can provide continuous bias to chronically-implanted sites. The sites, which were biased at 0.5V and –0.5V, exhibited considerable tissue growth on them after three weeks in guinea pig. Further studies will be done at lower voltages.

We have continued to optimize circuitry for use in a wireless probe interface. Circuitry for power-on-reset, clock generation, envelope detection, and voltage regulation has been redesigned to decrease power consumption and has been layed out in 1.6μm technology consistent with a popular MOSIS process. The total power dissipation of these blocks is now only 3.5mW. Fabrication of additional wafers containing PIA-2B/3B probes has also been completed. A problem leading to low-yield on some of these wafers was traced to incomplete etch of the polysilicon leads connecting the shank sites to the input site selection circuitry. The etch will be lengthened on future runs to eliminate the problem. The 96-site buffered probes also fabricated on these wafers have been tested in-vitro and in-vivo and will soon be provided to external users. In the meantime, we are iterating the PIA-2B masks to make minor circuit changes and add preamplifiers with gain in place of the present buffers. We are also proceeding to complete redesign of the circuitry for PIA-2 and PIA-3, our multiplexed recording probes.